A 'Stitched' Flexible Light Weight Multilayer 16x16 Antenna Array on LCP

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***Abstract*— This paper presents a light weight multilayer 14 GHz antenna array on an organic LCP (Liquid Crystal Polymer) substrate. The antenna structure includes a two layer corporate feed network, which is partially embedded, connected with vias, otherwise known as 'stitched'. First, using 4x4 microstrip patch arrays as the unit array, a 6.5° beam steer is observed when a 90° phase difference is applied to a 4x8 antenna array. The stitched 4x8 antenna array has a 3 dB beamwidth of 12° and a maximum gain of 15.4 dB with no phase shift, and the gain drops to 13 dB with a phase shift. Next, a 16x16 antenna has been constructed applying the stitching concept. The results show a 3 dB beamwidth of 6° and a 16.8 dB of gain.**

I. Introduction

As the demand for smaller devices grows, multilayer integration has become a key concept to optimize the compactness in a design. One application that can benefit from the multilayer approach is arrayed antennas. Antenna arrays give the advantage of high directivity and gain, which are essential for military and space applications. At 14 GHz, large antenna arrays are used for precipitation observation in the atmosphere [1], [2]. For these applications, the size of the array can increase very quickly, thus, multilayer configurations can help decrease the size. By separating the elements of the antenna array from the feed network and active components in the system to different layers, the compactness of the design can be maximized. Furthermore, reducing the overall size in a single layer can give rise to coupling between the feeding elements and radiating elements. Again, the multilayer approach can help eliminate this problem by incorporating an embedded ground. Previous sudies have demonstrated multilayer flexible antenna arrays with embedded ground, which also includes slots for the coupling between the feeding elements and radiating elements [3]. In addition, integration of a phase shifter to make a compact reconfigurable phased antenna array and a 'stitching' technique to expand the array beyond available fabrication limits have been explored [4], [5].

In this paper, light weight and flexible multilayer antenna arrays on LCP are presented. The 4x8 antenna array that is hardwired, or fixed in phase, with a phase shifter for each 4x4 unit array shows a maximum of 6.5° beam steering in either direction. The array has a 3 dB beamwidth of 12° with a maximum gain of 15.4 dB and a gain of 13 dB when steered. In addition, a 16x16 antenna array with a 3 dB beamwidth of 6° and gain of 16.85 dB is presented. A significant advantage of these arrays is that they can be conformed to various surfaces, thus reducing the installation cost.

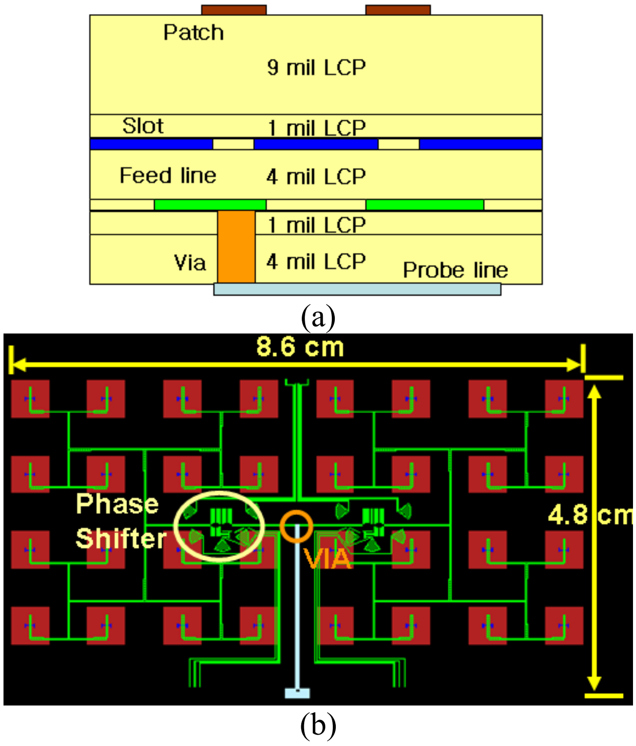

Fig 1. (a) Stack up of the antenna array (b) a composite view of 4x8 layout

II. Antenna Design

A. *Physical structure*

Fig. 1 (a) shows the details of the multilayer stack up from a side view, while Fig. 1 (b) shows the corresponding layout of a 4x8 antenna array from a top view. The operating frequency of the antenna is 14 GHz. As seen in Fig. 1 (a) the

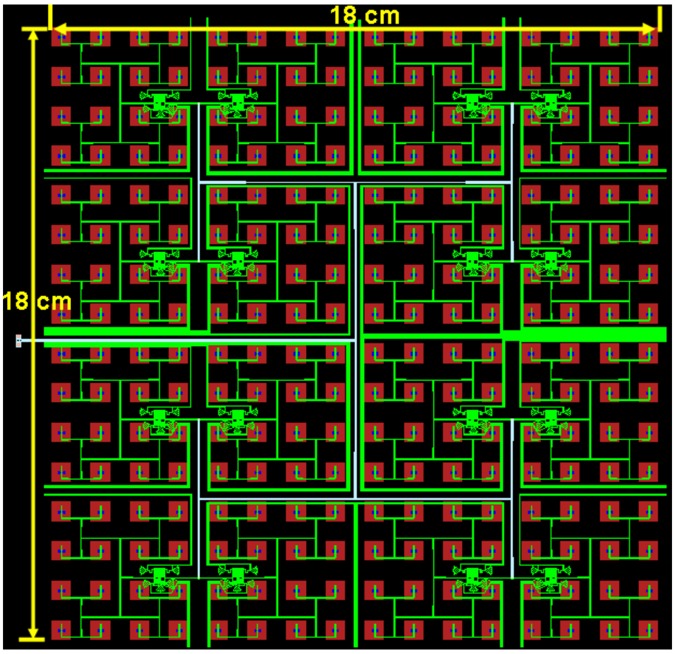

Fig. 2. 16x16 antenna array layout.

probe line layer is connected to the embedded feed line layer through a 250 μm diameter and 5 mil tall via. The signal is then fed to the patches through the slot layer that also acts as a ground plane for the microstrip lines in both the probe line and feed line layers. The patch layer is 10 mils above the slot layer. The square patch sides are 0.48λ and each patch is separated by 0.52λ. LCP is particularly useful in designing such antenna structures as it has a low dielectric constant ($\varepsilon_r \approx$ 2.95) and it is relatively easy to fabricate multilayer designs. The 1 mil LCP layers act as bonding layers between the 4 mil and 9 mil core layers. This is enabled through the physical properties of LCP in which the 1 mil bond ply LCP melts around 285 ^{o}C and the thicker core layers melt around 315 ^{o}C.

In Fig. 1 (b), we can see the antenna structure includes a partially embedded corporate feed network which includes area for embedding RF components. In this case, a hardwired, or fixed phase, 2 bit phase shifter is included in the feed line layer. This is a preliminary design for MEMS enabled phase shifters that include the bias lines routed to the edges. Each 4x4 unit array includes a single 2 bit phase shifter. The overall size of the 4x8 antenna is 8.6 cm by 4.8 cm.

Fig. 2 shows the layout of the 16x16 antenna design. Again, as a preliminary version of a MEMS phased array, the hardwired phase shifters are included with long bias lines routed to the edges of the antenna. The overall size is 18 cm by 18 cm. Even with a thickness of 19 mils, the antenna array maintains its flexibility and with a low specific gravity (SG ≈ 1.4 g/cm^3) it sustains its light weight.

B. Directivity and Gain Calculation

From equation (1), we can estimate the directivity from the 3 dB beam widths

$$D_o \approx \frac{22.181}{\Theta_{1r}^2 + \Theta_{2r}^2} \qquad (1)$$

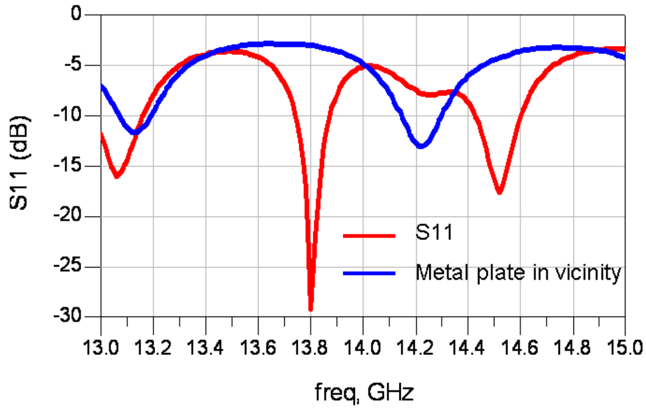

Fig. 3. Return loss measurement of the 4x8 antenna array with no phase shift to verify the radiation.

where D_o is the maximum directivity and Θ_{1r} and Θ_{2r} are the 3 dB beam widths in radians of the *E*- and *H*-planes [6].

The ideal gain of the antenna array can be estimated from the following equation

$$G = \varepsilon_{ap}\frac{4\pi}{\lambda^2}A_p = \varepsilon_{ap}\frac{4\pi}{\lambda^2}Nd^2 \qquad (2)$$

where ε_{ap} is the efficiency, A_p is the area of the aperture, N is the number of elements, and d is the antenna spacing [7]. Thus, assuming ideal aperture efficiency of 1, the 4x8 antenna array with 32 patch elements should have a gain of 20.36 dB. Additionally, the 16x16 antenna array should have an ideal gain of 29.39 dB.

III. Measurement

All measurements were done in comparison to a 10 dBi horn antenna at 13.8 GHz. Due to fabrication tolerances, there has been a slight shift in the operating frequency. In addition, a correction factor of about 0.5 dB needs to be added because the arrays were excited using a probe, which has about 0.7 dB loss at our operating frequency, opposed to a connector that has about 0.2 dB of loss.

A. 4x8 Antenna Array

Fig. 3 shows the measured S11 response of the 4x8 antenna array with no phase shift. The sharp resonance shows the operating frequency of the antenna array. The other line shows the response when a metal plate is set in the vicinity of the patches, thus, reflecting all radiation energy. The result shows that the steep resonance disappears with the metal plate near the radiating elements, which verifies that the antenna array is working properly at 13.8 GHz. The remaining dips in the response do not disappear with the placement of the metal plate, which means that they are resonances derived from the parasitic inductance and capacitances.

Fig. 4 shows the measured antenna pattern of a 4x8 antenna with the two phase shifters having three different states. First is the state in which both phase shifters have the same phase shift of 0^o shown as the middle pattern of the three. The resulting pattern shows a 3-dB beamwidth of 12^o in the *H*-plane and approximately 24^o in the *E*-plane. Using equation (1), we can calculate the directivity to be 20.04 dB, which is

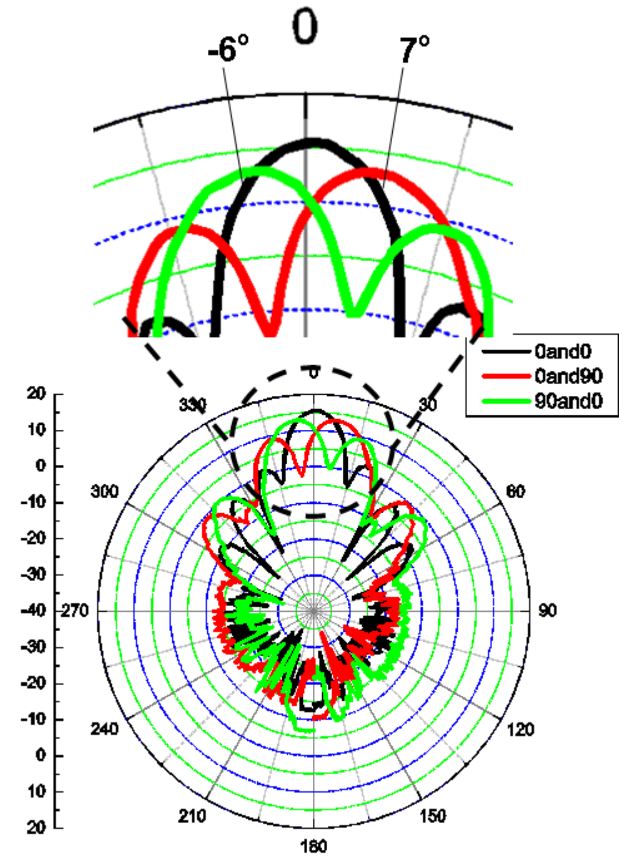

Fig. 4. 4x8 antenna pattern measurement of the Hco field with and without 90 degrees phase shift.

close to the ideal gain calculation for the 4x8 antenna array.The SLL (Side Lobe Level) is 13 dB below the maximum, and the maximum gain is 15.4 dB. The gain is approximately 5 dB lower than the ideal gain because of the line loss from the feeding network and possible leakage in the slot coupled feed of the patches. A rough estimate can be made to verify the loss that has been measured. The microstrip line length from the feed point to the antenna is approximately 9.5 cm. With a line loss of 0.25 dB/cm on LCP [8], about 2.37 dB is contributed to the line loss. The meander lines in the phase shifter roughly add 0.2 dB of loss. In addition, with slight fabrication errors, each T-junction adds about 0.3 dB of loss contributing to an additional 1.5 dB loss. The simulated via adds an additional 0.4 dB of loss as a square patch twice the size of the via is added as a landing pad. Thus, including the error factor, the total loss is 4.97 dB, which is close to the calculated ideal gain. In addition to these estimated numbers, additional loss can be attributed to leakage from the coupling slots.

When a 90^{o} phase shift is applied to either side of the 4x8 array, the resulting beam steers approximately 6.5^{o} away from the maximum. The gain drops significantly to 13 dB and the SLL rises to only 4.2 dB lower than the main lobe, almost splitting the main beam. This can be avoided if the phase shift is applied to a smaller unit array such as a 2x2 or ideally every element, which will also increase the maximum beam steer angle.

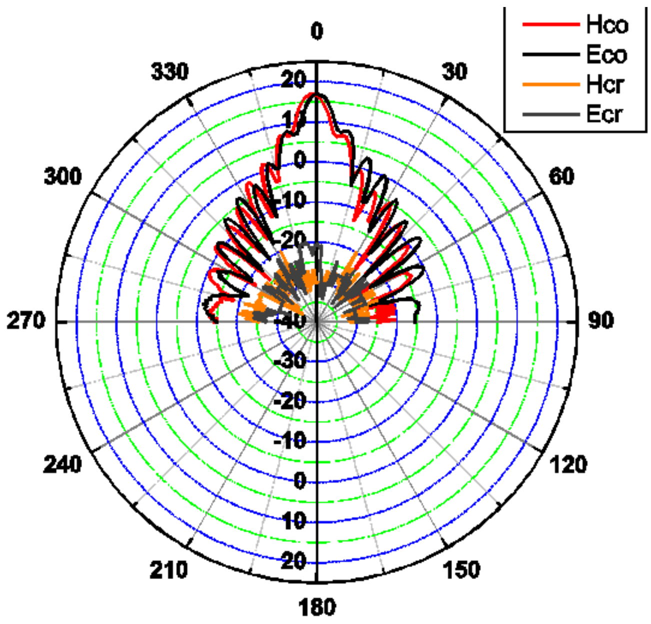

Fig. 5. 16x16 antenna pattern measurement.

B. *16x16 Antenna Array*

Fig. 5 shows the pattern measurement of the 16x16 antenna array. The 3 dB beam width, in both the *E*- and *H*-plane, is measured to be 6^{o} and the SLL is approximately 9 dB below the main beam. The calculated directivity is 30.04 dB, which again is similar to the estimated ideal case. As expected, the beam is more directive than that of the 4x8 array. The maximum gain is 16.85 dB which is relatively low compared to the calculated ideal gain of 29.39 dB. The loss of 12.54 dB can again roughly be verified by estimated calculations. The total length from the feed point to the antenna is roughly 29 cm and with 0.25 dB/cm of loss, the total line loss is estimated to 7.25 dB. There are eight T-junctions that amount to 2.4 dB of loss. The phase shifter, via, and error factor roughly adds 1.1 dB of additional loss. The total estimated loss is 10.85 dB, which still is 1.7 dB lower than the ideal case. Other than the antenna efficiency and the loss from the coupled slots, additional loss can be contributed to the more complex feed network compared to the 4x8 array. The long bias lines that run in the embedded layer along the bottom probe line layer can also introduce additional loss. In order to minimize the coupling between layers and lines, the length of the thinner sections ($Z_o = 70.7\,\Omega$) in the T-junctions have been elongated, which in return becomes more lossy. These values are estimated values to verify the plausibility of the measured gain.

Fig. 6 shows a picture of the fabricated 16x16 antenna array. The details of the slot and feed line including the phase shifter are omitted since they are embedded.

Experimental results of the array performance while it is conformed to different curved surfaces are currently under way and will be presented at the conference.

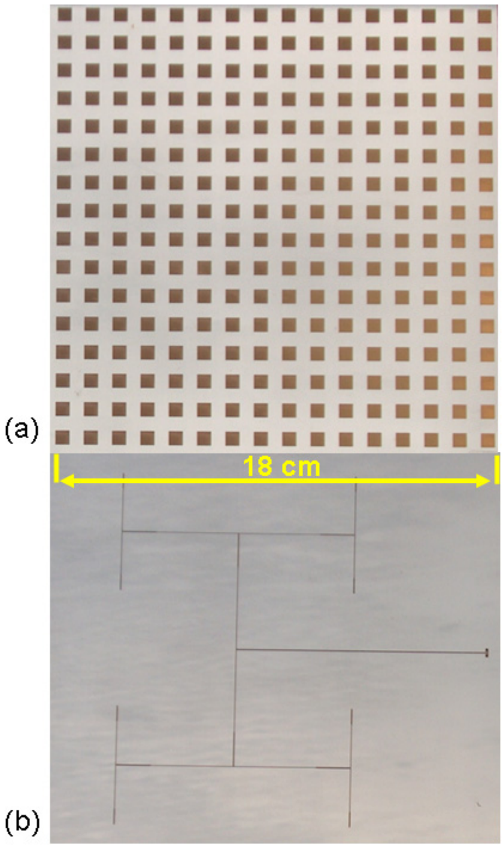

Fig. 6 Fabricated 16x16 antenna (a) Patch layer (b) Probe layer.

IV. Conclusions

A light weight flexible multilayer antenna array on LCP has been presented. A 4x8 antenna array with 15.4 dB of gain and 3 dB bandwidth of 12^o is shown along with two more 4x8 arrays with a 90^o phase shift in either direction to obtain 6.5^o beam steer. A 16x16 antenna array is also presented that shows 16.85 dB maximum gain with a 3 dB bandwidth of 6^o. The small additional gain of the 16x16 antenna array compared to the 4x8 antenna array shows that the array is reaching its size limitations as the loss from the lengthy feed network is becoming dominant. Results of the arrays when flexed will be presented at the conference.

References

[1] K. D. Le, R. D. Palmer, B. L. Cheong, T. Y. Yu, G. Zhang, and S. M. Torres, "On the use of auxiliary receive channels for clutter mitigation with phased array weather radars," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 47, No.1, January 2009.

[2] E. Im, S. L. Durden, and S. Tanelli, "Recent advances in spaceborne precipitation radar measurement Techniques and Technology," *IEEE Conference on Radar*, April 2006.

[3] G. DeJean, R. Bairavasuramanian, D. Thompson, G. E. Ponchak, M. Tentzeris, and J. Papapolymerou, "Liquid Crystal Polymer (LCP): a new organic material for the development of multilayer dual-frequency/dual-polarization flexible antenna arrays," *IEEE Antennas and Wireless Propagation Letters*, vol. 4, 2005.

[4] D. J. Chung, D. E. Anagnostou, M. Tentzeris, and J. Papapolymerou, "Integration of a 4×8 antenna array with a reconfigurable 2-bit phase shifter using RF MEMS switches on multilayer organic substrates," *IEEE Antennas and Propagation International Symposium*, 9-15 June 2007, Pages 93 -96

[5] D. J. Chung, S. Bhattacharya, G. Ponchak, and J. Papapolymerou, "A Stitching Technique for Expanding Large 3-D Multi-layer Antenna Arrays in Ku-band using Small Array Units," *Electronics Components and Technology Conference*, May 2008, Pages 175-178.

[6] C. A. Balanis, *Antenna Theory* 3rd edition, John Wiley & Sons, Inc, Hoboken, NJ, 2005.

[7] W. L. Stutzman and G. A. Thiele, *Antenna Theory and Design* 2nd edition, John Wiley & Sons, Inc, Hoboken, NJ, 1998.

[8] D. Thompson, J. Papapolymerou, and M. M. Tentzeris, "High Temperature Dielectric Stability of Liquid Crystal Polymer at mm-Wave Frequencies," *IEEE Microwave and Wireless Components Letters*, vol. 15, No. 9, September 2005.